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Carbon dynamics and sequestration in an irrigated Vertisol in Central Mexico

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Abstract

Conservation tillage could enhance soil organic carbon (SOC) sequestration, but is rarely used in cropping systems in Mexico, especially under irrigation. A study was conducted on a clayey, smectitic, isothermic Udic Pellustert to evaluate the use of traditional-deep and no-tillage systems on SOC dynamics for wheat (*Triticum aestivum* L.)–corn (*Zea mays* L.) and wheat–bean (*Phaseolus vulgaris* L.) cropping systems. Experimental design was a randomized block of five tillage/crop-rotation (two crops per year) systems with four replications: (WC-CTb) wheat–corn, burning the residues of both crops, plowing and disking twice (WC-CT) wheat–corn under conventional tillage (plowing and disking twice to incorporate crop residues following the harvest of each crop), (WC-NT) wheat–corn under no-till, (WB-CT) wheat–bean under conventional tillage, and (WB-NT) wheat–bean under no-till. Each crop in the sequence received one of three fertilizer-N rates broadcast as urea: (a) 0, 150, and 300 kg N ha^{-1} for corn; (b) 0, 40, and 80 kg N ha^{-1} for bean; and (c) 0, 125, and 250 kg N ha^{-1} for wheat. The baseline year was 1994, and relative changes were measured from 1994 to 1999 for grain yield and residue production, crop residue C and $\delta^{13}C$, SOC, soil C/N ratio, and change in soil $\delta^{13}C$. Interaction of cropping system × fertilizer-N rate was highly important to grain yield and crop residue production and amount of crop-residue C produced. High N rates increased SOC sequestration and decreased soil C/N ratios. In WC systems, more negative $\delta^{13}C$ was associated with higher N rates, indicating increased contribution of wheat (a C_3 plant) residue C relative to corn (a C_4 plant). In WB, N-rate and tillage had no effect on SOC sequestration. Highest rate of SOC sequestration was under WC-NT and when increases in SOC from 1994 to 1999 were annualized was 1.0 and 1.9 Mg SOC yr^{-1} in the 0–15- and 15–30-cm depths, respectively. Corresponding SOC in 0–15- and 15–30-cm depths in the WC-CT treatment was 0.2 and 0.6 Mg yr^{-1} and amounts in all other treatments were equal or lower than those observed for WC-CT. There was a significant correlation between aboveground crop-residue C produced and amount of SOC sequestered. Results from this study indicate no-till on N-fertilized WC systems can potentially increase SOC sequestration on large areas of irrigated Vertisols in Central Mexico while maintaining high crop yields.

Keywords: Soil organic C; C sequestration; Cropping systems; Wheat–corn rotation; N fertilization; Vertisols

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1. Introduction

In Mexico, there are >3 Mha of Vertisols under irrigation that represent ~38% of all irrigated land in Mexico (Ortiz and Ortiz, 1990; SAGARPA, 2000). Vertisols are a major soil resource in Mexico for the production of both feed and food crops. The main crops planted on these soils are corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and wheat (*Triticum aestivum* L). A typical cropping sequence under irrigation can include a winter crop of wheat followed by a summer crop of corn or sorghum. Bean (*Phaseolus vulgaris* L.) is an important food crop often included as a summer crop in the sequence.

Carbon in Vertisols is a major component of soil organic matter (SOM). Higher amount of SOM is generally recognized to enhance water holding capacity, help support an active microbial biomass for nutrient retention and supply, especially for N, decrease nitrate leaching, and for retaining applied pesticides (Follett et al., 1995). One of the most important terrestrial pools for C storage and exchange with atmospheric CO_2 is soil organic C (SOC) (Lal et al., 1998, 1999). Long-term records indicate that, following the advent of large-scale cultivation, SOC in soils of the state of Guanajuato Mexico were reduced from ~30 g kg^{-1} in the top 20 cm (Sergio Enriquez, personal communication) to about 18 g kg^{-1} (Castellanos et al., 2000). Typically, for at least 50 years crop residues have been burned and soils deeply and frequently plowed. During periods of time when cultivated Vertisols are without residue cover there is an accompanying increase in temperature of the soil surface (Dalal and Carter, 2000) and increased rate of SOM decomposition. Webb et al. (1977) measured a 15% decline in SOC (0–100-cm depth) on an Australian Vertisol from 26 to 22 g kg^{-1} after forest clearing.

Generally recognized is that if amount of C entering the soil exceeds that which is lost, SOC content increases. Increased SOC can result from: (1) improved cropping systems, (2) management to increase quantity of residues produced and degree of residue cover, and (3) efficient use of production inputs such as N and water (Follett, 2001). Adoption of these and other best management practices should enhance SOC sequestration while helping achieve soil conservation and water quality goals and mitigate CO_2 emission effects on climate change (Lal et al., 1998, 1999). The primary source for C input is from plant residue C (including roots and crowns). Possible outputs of C include microbial respiration and plant residue and SOM decomposition, leaching of soluble C, and SOC transport with eroding sediments (Follett, 2000).

Among tillage systems that conserve residue C and potentially increase amount of C sequestered is conservation tillage (e.g., no-till, ridge-till, and mulch-tillage) (Lal et al., 1998, 1999). However, conservation tillage is rarely practised on soils in Mexico. Research of this type is needed on Vertisols to improve understanding of cropping-system effects on C sequestration. The objective of this study was to evaluate C dynamics and potential for wheat–corn and wheat–bean cropping systems to rebuild SOC in an irrigated Vertisol of central Mexico.

2. Materials and methods

This study was conducted on a clayey, smectitic, isothermic Udic Pellustert at the Bajio Research Station, located at the National Institute of Agricultural, Forestry, and Livestock Research (INIFAP), near Celaya, Gto, in the Center of Mexico (20.52°N, 100.82°W). The Vertisol soil order has a high content of swelling-type clays and during dry periods can develop cracks, which give rise to a partial inversion of the soil (Soil Survey Staff, 1998). Prior to treatment establishment, the experimental field (conventionally farmed) was planted to winter wheat (fall of 1993) followed with a summer crop of sorghum (spring of 1994). Both crops were irrigated and fertilized at 250 kg N ha^{-1}. Following conventional tillage, experimental treatments were established in fall of 1994 with planting of winter wheat. Experimental design was a randomized block of five tillage and crop-rotation (two crops per year) treatments, hereafter referred to as cropping systems with four replications: (WC-CTb) wheat–corn, burning the residues of both crops, plowing and disking twice, (WC-CT) wheat–corn under conventional tillage, plowing and disking twice to incorporate crop residues following the harvest of each crop, (WC-NT) wheat–corn under no-till, (WB-CT) wheat–bean under conventional tillage, plowing and disking twice to incorporate crop residues following the harvest of each crop, and (WB-NT) wheat–bean under no-till. Plowing was to 20-cm depth using moldboard plow. Seeding rate was 180 kg ha^{-1} for wheat, ~160,000 seeds ha^{-1} for bean, and 75,000 seeds ha^{-1} 1 for corn, except in 1996 when corn was planted at 100,000 seeds ha^{-1}.

Each of the five cropping systems was split to receive one of three fertilizer-N rates (broadcast as urea) and hereafter referred to as N0, N1, or N2, respectively: (a) 0, 150, and 300 kg N ha^{-1} for corn; (b) 0, 40, and 80 kg N ha^{-1} for bean; and (c) 0, 125, and 250 kg N ha^{-1} for wheat. Phosphorus fertilizer was broadcast uniformly as triple super phosphate across all treatments prior to planting of every crop (twice yr^{-1}) at 60 kg P_2O_5 ha^{-1}. Weeds in wheat were controlled after planting with fenoxaprop-p-etil at a rate of 69 g a.i. ha^{-1} and 2,4-D amine at a rate of 720 g a.i. ha^{-1}. Weeds in corn were controlled with atrazine + metalachlor at a rate of 1.5 + 1.5 kg of a.i. ha^{-1} prior to planting and 2,4-D at the same rate after planting as in wheat. Weeds in bean were controlled 15 days after emergence with fomesafen at a rate of 300 g a.i. ha^{-1} plus fluazifop-p-butil at 480 g a.i. ha^{-1}.

Plots were 0.03 ha in size. Corn and bean were border irrigated three times and wheat was border irrigated five times including at planting. Precipitation was 25–50 cm yr^{-1}, with nearly all occurring between June and October. Irrigation was applied to supplement precipitation so that approximate evapotranspiration requirements of each crop were met. The first irrigation was 20 cm of water and subsequent irrigations were 12 cm each.

Aboveground crop yields (grain and crop residue) were obtained by sub-sampling a representative area of 4.8 m^2 at time of harvest in 1995, 1996, and 1997 for summer crops and 1996, 1997, and 1998 for winter crops. Plants from all treatments (including WC-CTb, before residue burning) were clipped at a 5 cm height, separated into grain and crop residue, and oven dried at 55 °C. The grain of corn, wheat, and bean were adjusted to 15.5, 12, and 14% moisture, respectively.

Soil was collected in the spring following wheat harvest in 1999 from 0 to 15- and 15 to 30-cm depths from a composite of at least twelve 8-cm diameter soil cores per plot. Baseline samples for this study were collected in the spring of 1994. Soil bulk density samples were collected from within each main plot by excavating all of the soil from 30 cm × 30 cm pits (sampled in 15-cm depth increments) and then drying and weighing it. Sampling was at the same time as for the collection of other soil samples.

Following collection, soil samples were oven-dried at 55 °C, ground to pass a 180 μm screen and acid checked for free carbonates; free carbonates did not occur in either the 0–15- or the 15–30-cm depth samples. Soil was analyzed for total SOC, total soil N (TSN), and $\delta^{13}C$ using an ANCA-NT System, solid/liquid preparation module coupled to a 20–20 stable isotope analyzer (PDZ Europa Ltd., Crewe, England).[1]

Subsamples of wheat, corn, and bean residues were collected at harvest, ground to pass a 150 μm screen, and analyzed for C and $\delta^{13}C$. Eq. (1) expresses the $^{13}C/^{12}C$ ratio as $\delta^{13}C$ in 'per mil' (‰) units. By convention, $\delta^{13}C$ values are expressed relative to a calcium carbonate standard known as 'PDB' from the Cretaceous Pee Dee formation in South Carolina (Boutton, 1991). The sign of the $\delta^{13}C$ value indicates whether the sample has a higher or lower $^{13}C/^{12}C$ isotope ratio than PDB. Photosynthetic pathways of C_3 (wheat and bean) and C_4 (corn) plants discriminate differently for the naturally occurring ^{13}C isotope so that the $^{13}C/^{12}C$ isotope ratio can be used to help identify the origin of the C in the SOM. Where plants with different photosynthetic pathways grow in a time sequence in managed or unmanaged systems, or concurrently in the same system, the SOM will contain two isotopically different sources of plant C (Martin et al., 1990; Balesdent and Balabane, 1992; Gregorich et al., 1995a, 1995b, 1996; Hsieh, 1996). Gregorich et al. (1996) also used ^{13}C abundance methods to account for the higher amount of C_4 plant-derived C in long-term N fertilized soils compared to unfertilized soils.

$$\delta^{13}C(‰) = \frac{(^{13}C/^{12}C)\,\text{sample} - (^{13}C/^{12}C)\,\text{reference}}{(^{13}C/^{12}C)\,\text{reference}} \times 1000 \quad (1)$$

Use of the $^{13}C/^{12}C$ isotope ratio, C content and mass of plant material allowed the masses of ^{13}C and ^{12}C to be calculated for the aboveground crop residues for each

[1] Trade and company names are included for the benefit for the reader and do not imply endorsement or preferential treatment of the product by the authors, USDA, or INIFAP.

crop at each harvest. Total masses of ^{13}C and ^{12}C isotopes in the crop residues were calculated as an average $\delta^{13}C$ of the crop residues that were returned to each research plot. Calculations of aboveground crop-residue C and its C isotope content, expressed as $\delta^{13}C$, could be related to soil $\delta^{13}C$ values.

Statistical evaluation was by general linear modeling, means separation, correlation, and regression procedures (SAS Institute, 1988). Separation of means was by Tukey's pair wise procedure.

3. Results and discussion

3.1. Aboveground plant material

3.1.1. Grain yield and residue production

Cropping system and fertilizer-N rate interacted for both grain yield and crop-residue production (Table 1). Corn grain yield increased significantly with each additional increment of added N. At N0, there was no significant difference among WC systems for corn or wheat grain yields or for corn residue production. However, WC-NT generally had higher wheat residue production than WC-CT at N0 and N1. The WC-CTb generally had higher corn and wheat grain yield at the N1 and N2 rates than WC-CT and WC-NT. Corn residue production was lower for WC-NT than for WC-CT at N1 and not different among systems at N2. Wheat residue production was lower for WC-CT than WC-CTb at N1 and not different among systems at N2.

Bean grain yield and residue production were little influenced by N rate, although both tended to be higher under WB-CT than WB-NT (Table 1). Bean is sensitive to lack of oxygen and under WB-NT such conditions may have occurred. In WB systems, both wheat grain yield and residue production increased significantly with each additional increment of N.

A significant cropping system × year interaction was observed for both corn grain yield and residue production, with both lower in 1996 than in 1995 and 1997 because of lodging with high planting rate and winds in 1996 (Table 2). Although there were differences in corn grain yield and corn residue production among years, there were generally no differences among years for bean grain yield and residue production. A significant interaction of fertilizer-N rate × year was observed for wheat grain yield, but not for residue production (Table 2).

Table 1
Crop grain yield and residue production for summer crops (corn and bean) harvested in 1995, 1996, and 1997 and winter crop (wheat) harvested in 1996, 1997, and 1998 for five cropping systems and three fertilizer-N rates[a,b]

Cropping system	N-rate	Summer crop ($Mg\ ha^{-1}\ yr^{-1}$)		Winter crops ($Mg\ ha^{-1}\ yr^{-1}$)	
		Grain	Residue	Grain	Residue
WC-CTb	N0	2.6 e	6.7 d	1.9 j	3.0 ij
WC-CTb	N1	6.8 b	10.3 bc	4.6 ef	8.3 ef
WC-CTb	N2	8.7 a	12.4 a	6.5 a	11.2 abc
WC-CT	N0	2.7 e	6.2 d	1.8 j	2.2 j
WC-CT	N1	6.0 c	10.5 b	3.6 gh	5.3 gh
WC-CT	N2	8.7 a	12.7 a	5.7 bcd	10.5 bcd
WC-NT	N0	2.6 e	5.8 d	2.0 j	4.3 hi
WC-NT	N1	5.1 d	9.1 c	4.0 fg	6.9 fg
WC-NT	N2	7.4 b	12.1 a	5.8 abcd	10.5 bcd
WB-CT	N0	2.0 fg	2.1 e	3.2 hi	5.0 gh
WB-CT	N1	2.0 fg	2.2 e	5.2 de	9.1 de
WB-CT	N2	2.2 ef	2.3 e	6.0 abc	12.2 ab
WB-NT	N0	1.39 g	1.6 e	2.8 i	4.9 ghi
WB-NT	N1	1.45 g	1.7 e	5.4 cd	10.0 cde
WB-NT	N2	1.44 g	1.8 e	6.4 ab	12.9 a

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till. Each crop in a sequence received one of three N-fertilizer rates where N0, N1, and N2 was 0, 150, and 300 kg N ha^{-1} for corn; 0, 40, and 80 N ha^{-1} for bean; and 0, 125, and 250 N ha^{-1} for wheat.

[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

3.1.2. Crop-residue carbon

The interaction of cropping system × fertilizer-N rate was significant for total amount of aboveground residue C produced and the average $\delta^{13}C$ of aboveground residue C from 1995 to 1998 (Table 3). Increasing N rate increased crop-residue production more in WC systems than in WB systems, likely as a result of the high potential for corn to respond to N, and the self-sufficiency with biological N fixation in bean. N rate increased total crop-residue C production for the WB systems (avg. = 7.2, 12.2, and 15.4 Mg ha^{-1} at the N0, N1, and N2 rates, respec-

Table 2
Crop grain yield and residue production for summer crops (corn and bean) harvested in 1995, 1996, and 1997 for five cropping systems and for winter crop (wheat) harvested in 1996, 1997, and 1998 for three fertilizer-N rates[a,b]

Cropping system	Summer crop ($Mg\ ha^{-1}\ yr^{-1}$)			Winter crop ($Mg\ ha^{-1}\ yr^{-1}$)		
	Year	Grain	Residue	N-rate	Year	Grain
WC-CTb	1995	5.9 c	9.4 c	N0	1996	2.8 cd
WC-CTb	1996	4.5de	7.4 d	N1	1996	5.1 b
WC-CTb	1997	7.8 a	12.5 a	N2	1996	6.7 a
WC-CT	1995	6.4 bc	11.1 abc	N0	1997	2.4 de
WC-CT	1996	3.6 ef	6.8 d	N1	1997	5.2 b
WC-CT	1997	7.4 ab	11.4 ab	N2	1997	7.2 a
WC-NT	1995	5.1 cd	10.2 bc	N0	1998	1.8 e
WC-NT	1996	3.9 de	6.8 d	N1	1998	3.4 c
WC-NT	1997	6.2 bc	10.0 ab	N2	1998	4.4 b
WB-CT	1995	2.4 fg	2.7 e			
WB-CT	1996	2.3 fg	1.9 e			
WB-CT	1997	1.5 gh	1.9 e			
WB-NT	1995	1.5 gh	2.02 e			
WB-NT	1996	1.8 fg	1.86 e			
WB-NT	1997	0.9 h	1.30 e			

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till. N-fertilizer rates = 0, 125, and 250 N ha^{-1} for wheat.
[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

Table 3
Cumulative crop-residue C and average $\delta^{13}C$ for aboveground crop-residues produced during the 1995–1998 growing seasons for five cropping systems and three fertilizer-N rates[a,b]

Cropping system	N-rate	Total crop-residue C ($Mg\ ha^{-1}$)	Average $\delta^{13}C$ of residues (‰)
WC-CTb	N0	10.5 de	−16.0 ab
WC-CTb	N1	20.1 b	−17.9 c
WC-CTb	N2	25.5 a	−18.3 c
WC-CT	N0	9.3 ef	−15.3 a
WC-CT	N1	17.2 c	−16.4 b
WC-CT	N2	25.1 a	−18.0 c
WC-NT	N0	11.0 de	−17.7 c
WC-NT	N1	17.2 c	−17.7 c
WC-NT	N2	24.5 a	−18.2 c
WB-CT	N0	7.5 fg	−26.5 d
WB-CT	N1	11.9 d	−26.4 d
WB-CT	N2	15.2 c	−26.4 d
WB-NT	N0	7.0 g	−26.5 d
WB-NT	N1	12.2 d	−26.4 d
WB-NT	N2	15.4 c	−26.3 d

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till. Each crop in a sequence received one of three N-fertilizer rates where N0, N1, and N2 was 0, 150, and 300 kg N ha^{-1} for corn; 0, 40, and 80 N ha^{-1} for bean; and 0, 125, and 250 N ha^{-1} for wheat.
[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

tively) from the response of wheat to N. Also, although not measured, crop roots and crowns and weed residues not removed from the field or burned also could have provided additional plant C for decomposition and SOC sequestration.

Measured separately, plant residues from N0 had $\delta^{13}C$ values (mean ± 1 S.D.) of -26.2 ± 0.2, -27.3 ± 0.7, and -11.7 ± 0.2‰ for wheat, bean, and corn, respectively. The average $\delta^{13}C$ of crop materials at N0 for WC-CTb and WC-CT was significantly less negative (avg. = −15.6) than for WC-NT (−17.7) (Table 3). At N2, $\delta^{13}C$ of residues was not significantly different among WC systems (avg. = −18.2). With increasing N rate for WC-CTb and WC-CT, wheat residues contributed an increasing proportion to the combined crop-residue $\delta^{13}C$ signature. The relation of this effect to soil $\delta^{13}C$ is discussed below.

3.2. Soil analyses

3.2.1. Change in $\delta^{13}C$ (1994–1999)

The $\delta^{13}C$ of soil was determined in 1994 and 1999. In 1994, the $\delta^{13}C$ in the 0–15- and 15–30-cm depths was −19.5 and −19.1, respectively. The $\delta^{13}C$ across systems in 1994 was not different and averaged −19.4, except in WC-CT which was −18.7. The $\delta^{13}C$ across N-rates was not different and averaged −19.3. There was a significant interaction of cropping system × fertilizer-N rate on the changes in soil $\delta^{13}C$ (Table 4). In the WC system, contribution of wheat (a C_3 plant) to the change in the $\delta^{13}C$ signature from 1994 to 1999 relative to that from corn (a C_4 plant) increased as the rate of fertilizer N increased. Observed changes in $\delta^{13}C$ in the soil were consistent with aboveground crop-residue production and residue $\delta^{13}C$ (Tables 1 and 3) in that average corn residue

Table 4
The $\delta^{13}C$ and concentration of soil C in 1999 and change in $\delta^{13}C$ and concentration of soil C from 1994 to 1999 for five cropping systems and three fertilizer-N rates[a,b]

Cropping system	N-rate	Soil C (1999)		Soil C change (1994–1999)	
		$\delta^{13}C$	g kg^{-1}	$\delta^{13}C$	g kg^{-1}
WC-CTb	N0	−18.5 bcd	15.9 bcd	0.9 a	0.5 cd
WC-CTb	N1	−18.7 cde	15.4 cd	0.6 abc	0.1 d
WC-CTb	N2	−18.9 d	16.2 bcd	0.4 bc	0.8 bcd
WC-CT	N0	−18.0 a	14.8 d	0.7 ab	−0.2 d
WC-CT	N1	−18.3 ab	16.8 bc	0.4 bc	1.8 bc
WC-CT	N2	−18.4 bc	17.2 b	0.3 c	2.2 ab
WC-NT	N0	−18.5 bcd	17.3 ab	0.7 ab	1.9 abc
WC-NT	N1	−18.9 e	17.3 ab	0.3 c	1.9 abc
WC-NT	N2	−18.8 de	18.7 a	0.4 bc	3.3 a
WB-CT	N0	−19.9 fg	14.8 d	−0.2 d	0.6 cd
WB-CT	N1	−20.1 g	14.9 d	−0.5 d	0.7 cd
WB-CT	N2	−19.9 fg	14.9 d	−0.3 d	0.7 cd
WB-NT	N0	−19.9 fg	14.8 d	−0.3 d	−0.2 d
WB-NT	N1	−20.0 fg	14.8 d	−0.4 d	−0.3 d
WB-NT	N2	−19.7 f	15.3 d	−0.1 d	0.2 d

[a] WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till. Each crop in a sequence received one of three N-fertilizer rates where N0, N1, and N2 was 0, 150, and 300 kg N ha^{-1} for corn; 0, 40, and 80 N ha^{-1} for bean; and 0, 125, and 250 N ha^{-1} for wheat.

[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

production doubled from N0 (6.2 Mg ha^{-1} yr^{-1}) to N2 (12.4 Mg ha^{-1} yr^{-1}), whereas average wheat residue production tripled from N0 (3.2 Mg ha^{-1} yr^{-1}) to N2 (10.7 Mg ha^{-1} yr^{-1}).

A significant cropping system × profile depth interaction for $\delta^{13}C$ in the soil (Table 5) resulted from the 1994 to 1999 change in $\delta^{13}C$ in the 15–30 cm soil depth becoming more negative than in the 0–15-cm depth under WB systems, but no difference between depths in WC systems. In the case of WC-CTb, surface residues would not have been available for redistribution with depth. The WB systems had only C_3 crops that provided residue C with a more negative $\delta^{13}C$ signature than did WC systems. Movement of more negative $\delta^{13}C$ signature from wheat and bean residues into the 15–30-cm depth would be consistent with redistribution of residues by CT, but this same effect under NT may have also been possible with the basic characteristic of Vertisols having swelling-type clays that can result in development of cracks deep enough for materials from the upper part of the profile to slough into.

3.2.2. *Soil organic carbon concentration*

In 1999, SOC concentration was significantly influenced by the interaction between cropping system and fertilizer-N rate (Table 4). Both highest concentration of SOC in 1999 and the largest increase in concentration of SOC from 1994 to 1999 was observed for WC-NT. Neither SOC concentration nor SOC change were different among WC-CTb, WB-CT, and WB-NT systems regardless of N rate.

Increases in SOC concentrations were larger in the 15–30-cm depth than in the 0–15-cm depth (Table 5). The largest increase in SOC concentration (4.1 g kg^{-1}) was in the 15–30-cm depth of WC-NT and the changes in concentration of SOC in WC systems increased in the order of CTb, CT, and NT. No differences existed in the 0–15-cm depth among WC systems. The change in SOC concentration for WB systems was larger in the 15–30-cm depth than in the 0–15-cm depth, but showed no difference across CT or NT systems.

3.2.3. *Soil bulk density*

A cropping system by depth interaction on soil bulk density was observed both in 1999 and in the

Table 5
The $\delta^{13}C$ and concentration of soil C in 1999 and change in $\delta^{13}C$ and concentration of soil C from 1994 to 1999 for five cropping systems and two soil depths[a,b]

Cropping system	Depth (cm)	Soil C (1999)		Soil C change (1994–1999)	
		$\delta^{13}C$	g kg^{-1}	$\delta^{13}C$	g kg^{-1}
WC-CTb	0–15	−18.6 b	16.3 bcd	0.8 a	−0.1 de
WC-CTb	15–30	−18.8 b	15.4 cde	0.5 a	1.0 bcd
WC-CT	0–15	−18.3 a	16.5 bc	0.3 a	0.5 cd
WC-CT	15–30	−18.2 a	16.0 cde	0.6 a	2.0 b
WC-NT	0–15	−18.7 b	17.3 ab	0.6 a	0.6 bcd
WC-NT	15–30	−18.7 b	18.2 a	0.4 a	4.1 a
WB-CT	0–15	−20.0 c	14.9 e	0.1 ab	−0.3 de
WB-CT	15–30	−20.0 c	14.8 e	−0.7 b	1.6 bc
WB-NT	0–15	−19.9 c	15.0 de	0.2 a	−1.2 e
WB-NT	15–30	−19.9 c	14.9 e	−0.8 b	1.0 bcd

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till.
[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

change from 1994 to 1999 (Table 6). Soil was denser in the 15–30-cm depth than in the 0–15-cm depth in the WB and WC-CTb cropping systems. Change in bulk density from 1994 to 1999 was larger under WC-NT than under WC-CT at both depths and the largest increase from 1994 to 1999 was in WC-NT. Changes in bulk density from 1994 to 1999 for WB-CT and WB-NT systems were no different, nor were they different from those in the WC-CTb system.

Table 6
Soil bulk density in 1999 and change in soil bulk density from 1994 to 1999 for five cropping systems and two soil depths[a,b]

Cropping system	Depth (cm)	Bulk density (1999) (Mg m^{-3})	Bulk density change (1994–1999) (Mg m^{-3})
WC-CTb	0–15	0.98 cd	0.03 bc
WC-CTb	15–30	1.09 ab	0.07 abc
WC-CT	0–15	0.96 d	0.01 c
WC-CT	15–30	1.02 bcd	0.00 c
WC-NT	0–15	1.11 a	0.16 a
WC-NT	15–30	1.13 a	0.11 ab
WB-CT	0–15	0.97 d	0.02 bc
WB-CT	15–30	1.07 abc	0.04 bc
WB-NT	0–15	0.96 d	0.01 c
WB-NT	15–30	1.07 abc	0.05 abc

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till.
[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

3.2.4. Soil carbon:nitrogen ratio (C/N)

The C/N ratio in 1999 was highest for WC-CTb at N0 and least for WB-CT at N0 (Table 7). Across all N-rates, CT resulted in positive increases in C/N ratios indicating that incorporation and mixing of crop-residue materials increased the quantity of less decomposed SOM within the soil profile. The WC-NT system resulted in a lower C/N ratio (average = −0.8 units), as did the WB-NT system at N2 (−0.3 units), indicating more decomposed SOM. In 1999, C/N ratios were generally not different between the 0–15- and 15–30-cm depths and among all systems (Table 8). However, the C/N ratio from 1994 to 1999 declined in the 0–15-cm depth relative to the 15–30-cm depth under WC systems. Also, the C/N ratio from 1994 to 1999 declined more at the 0–15-cm depth compared to the 15–30-cm depth under NT than under CT systems. Residues remaining on the soil surface may have resulted in more decomposed SOM within the 0–15-cm depth than when incorporated by cultivation in the CT systems.

Table 7
Soil carbon to nitrogen (C/N) ratio in 1999 and the change in C/N ratio from 1994 to 1999 for five cropping systems and two fertilizer-N rates[a,b]

Cropping system	N-rate	C/N (1999) (ratio)	Change in C/N (1994–1999) (ratio)
WC-CTb	N0	12.0 a	0.6 ab
WC-CTb	N1	11.2 abc	−0.1 abcde
WC-CTb	N2	11.4 ab	0.0 abcde
WC-CT	N0	11.2 abc	0.3 abc
WC-CT	N1	11.4 ab	0.6 ab
WC-CT	N2	10.9 bc	0.0 abcd
WC-NT	N0	11.4 ab	−0.6 cde
WC-NT	N1	11.2 abc	−0.8 de
WC-NT	N2	11.1 abc	−0.9 e
WB-CT	N0	10.3 c	0.0 abcde
WB-CT	N1	11.0 bc	0.7 a
WB-CT	N2	10.9 bc	0.6 ab
WB-NT	N0	11.1 abc	0.2 abc
WB-NT	N1	11.2 abc	0.3 abc
WB-NT	N2	10.6 bc	−0.3 bcde

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till. Each crop in a sequence received one of three N-fertilizer rates where N0, N1, and N2 was 0, 150, and 300 kg N ha^{-1} for corn; 0, 40, and 80 N ha^{-1} for bean; and 0, 125, and 250 N ha^{-1} for wheat.

[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

Table 8
Soil carbon to nitrogen (C/N) ratio in 1999 and the change in C/N ratio from 1994 to 1999 for five cropping systems and two soil depths[a,b]

Cropping system	Depth (cm)	C/N (1999) (ratio)	Change in C/N (1994–1999) (ratio)
WC-CTb	0–15	11.5 abc	−0.2 c
WC-CTb	15–30	11.6 a	0.6 ab
WC-CT	0–15	11.0 abcd	0.0 abc
WC-CT	15–30	11.3 abc	0.6 a
WC-NT	0–15	10.9 bcd	−1.5 d
WC-NT	15–30	11.5 ab	−0.1 bc
WB-CT	0–15	10.9 cd	0.5 ab
WB-CT	15–30	10.6 d	0.3 abc
WB-NT	0–15	11.0 abcd	−0.2 c
WB-NT	15–30	11.0 abcd	0.3 abc

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till.

[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

3.2.5. Soil organic carbon sequestration

In 1999, total SOC was highest for the WC-NT system at N2 as was the change from 1994 to 1999 (Table 9). WC systems generally showed a positive response to N, but there was no response to N for WB systems. The change in SOC from 1994 to 1999 was largest for the WC-NT system, CT showed response to N, and CTb did not. Change in SOC from 1994 to 1999 for WB systems was positive, but no difference was observed between CT and NT, and response to N was not significant. Dalal (1989) in a no-till study with wheat grown for 10 years and barley for 3 years reported higher SOC and a positive interaction of tillage practice, crop-residue amount, and N-fertilizer for an Australian Vertisol. When increases in SOC in the 0–30-cm depth from 1994 to 1999 were annualized across N rate, lowest and highest rates of SOC sequestration were 0.3 and 2.8 Mg ha^{-1} yr^{-1} for WB-NT and WC-NT, respectively.

Rate of SOC sequestration within the 0–15-cm depth under no-till corn was 1.4–2.0 Mg C ha^{-1} yr^{-1} under high-fertility at sites in Colorado and Texas (Halvorson et al., 2004a,b). These studies included a conventional till treatment that showed a rate of 0.2 Mg C ha^{-1} yr^{-1} even with about the same level of crop residues that were produced under the no-till treatment.

As shown in Fig. 1, the 15–30-cm depth consistently had a higher rate of SOC accumulation than the 0–15-cm depth. The annualized rate of change in SOC from 1994 to 1999 across all treatments was 0.2 and 0.9 Mg SOC ha^{-1} yr^{-1} for the 0–15- and 15–30-cm depths, respectively. Highest rate of SOC sequestration, 1.9 Mg ha^{-1} yr^{-1}, occurred under WC-NT in the 15–30-cm depth while a loss of 0.3 Mg SOC ha^{-1} yr^{-1} was observed in the 0–15-cm depth under WB-NT. WC systems sequestered SOC in both the 0–15- and the 15–30-cm depths while WB systems showed increased SOC only in the 15–30-cm depth.

Table 9
Soil organic carbon (SOC) (0–30-cm depth) in 1999 and the change in SOC from 1994 to 1999 for five cropping systems and two fertilizer-N rates[a,b]

Cropping system	N-rate	SOC (1999) (Mg ha^{-1})	Change in SOC (1994–1999) (Mg ha^{-1})
WC-CTb	N0	49.5 cde	4.2 cd
WC-CTb	N1	47.9 cdef	2.5 cde
WC-CTb	N2	50.3 c	4.9 cd
WC-CT	N0	43.9 f	−0.4 e
WC-CT	N1	49.9 cd	5.6 c
WC-CT	N2	50.9 c	6.6 c
WC-NT	N0	58.3 b	12.9 b
WC-NT	N1	58.1 b	12.8 b
WC-NT	N2	62.8 a	17.5 a
WB-CT	N0	45.2 ef	3.3 cde
WB-CT	N1	45.4 def	3.6 cde
WB-CT	N2	45.4 def	3.6 cde
WB-NT	N0	45.3 ef	0.8 de
WB-NT	N1	45.2 ef	0.8 de
WB-NT	N2	46.7 cdef	2.3 cde

[a] WC-CTb = wheat–corn, burning the residues of both crops, plowing and disking twice following harvest of each crop; WC-CT = wheat–corn, plowing and disking twice following harvest of each crop to incorporate crop residues; WC-NT = wheat–corn under no-till; and WB-NT = wheat–bean under no-till. Each crop in a sequence received one of three N-fertilizer rates where N0, N1, and N2 was 0, 150, and 300 kg N ha^{-1} for corn; 0, 40, and 80 N ha^{-1} for bean; and 0, 125, and 250 N ha^{-1} for wheat.

[b] Within columns, values followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure).

3.3. Soil organic C and crop-residue C

To estimate SOC sequestration efficiency and amount of aboveground residue C to maintain SOC, the rate of SOC sequestration (Table 9) was divided by the rate of crop-residue production (Table 1) (times an assumed 40% crop-residue C concentration). The WC-CTb treatment was omitted because aboveground crop residues were burned.

The ratios of SOC to residue C for all replicates ($n = 48$) were sorted for *outliers* and to improve statistical *robustness* by *trimming* (Mosteller and Tukey, 1977; Venables and Ripley, 1999). Change in SOC to residue C ratio was most constant after removing four observations ($n = 40$) from each end of the data set and averaged 1.2 and 5.0 Mg ha^{-1} yr^{-1}, respectively. Linear regression of SOC against residue C following trimming resulted in Eq. (2), where: Y = Mg SOC ha^{-1} yr^{-1} and X = Mg crop-residue C ha^{-1} yr^{-1}:

$$Y = -0.47 + 0.33X, \quad r = 0.63^{**} \tag{2}$$

Eq. (2) allowed an estimate of: (1) amount of aboveground residue that, when produced each year, maintained SOC from decreasing and (2) crop-residue C sequestration efficiency. Solving Eq. (2) for the point at which change in SOC (Y axis) was equal to 0 resulted in a value of 1.4 Mg of aboveground crop-residue C ha^{-1} yr^{-1} that must be returned to maintain SOC in the 0–30-cm depth. There was considerable scatter among the data and, even though relationships for individual treatments might be derived, we feel it could be misleading and that additional research and better experimental control would be required. Importantly, these data indicate that a ‘‘threshold’’ amount of aboveground residue must be produced before net SOC sequestration becomes positive.

Average annual SOC sequestration rate (1.2 Mg C ha^{-1} yr^{-1}) divided by the annual rate of crop-residue C input (5.0 Mg C ha^{-1} yr^{-1}) provided a preliminary estimate of the C sequestration efficiency of 24%. It is important to note that this efficiency did not include contributions of crop crown and root material or of weeds for which we have little or no information. Follett et al. (1997) estimated for dryland, winter wheat fallow systems in the USA that a factor of about 2.2 times the weight of aboveground crop-residue C could be used to estimate total amount of residue C contained in above plus below ground crop- plus weed-residues. If the 24% efficiency were divided by the factor of 2.2, the estimate of the C sequestration efficiency would be 11%. In the study by Follett et al. (1997), the efficiency of residue C incorporation was observed to be between 5 and 10% from 84- and 20-year studies, respectively. Thus, a residue C sequestration efficiency of 11% for irrigated, double-crop systems in Mexico would be reasonable. In a study by Franzluebbers et al. (1998) in south central Texas, the portion of estimated C inputs sequestered with a cropping intensity of 2 crops yr^{-1} was ∼9% using conventional tillage, but ∼22% under no-till. These calculations show that knowledge of C mass in aboveground crop residues, plant roots, crowns, and weeds is critical to the estimation of plant residue C storage efficiency. Due to the relatively short time that

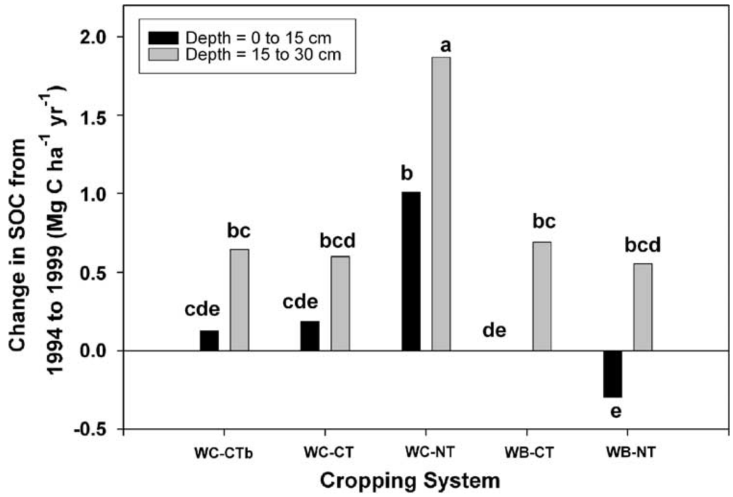

Fig. 1. Soil organic carbon sequestration rate from 1994 to 1999 as a function of cropping system within the 0–15- and 15–30-cm depths (averaged across N-rates). Bars with the same letter are not significantly different ($P \leq 0.05$; Tukey's pairwise procedure) (WC-CTb is wheat–corn, conventional tillage, residues burned; WC-CT is wheat–corn, conventional tillage; WC-NT is wheat–corn, no-till; WB-CT is wheat–bean, conventional tillage; and WB-NT is wheat–bean, no-till).

treatments were imposed, the range of crop residues produced, and wide differences in residue types in our study; these data should be considered an initial approximation of potential C sequestration efficiency for irrigated Vertisols in Mexico.

4. Summary

Cropping system and N fertilization were important to high grain yield and crop-residue production. Total yield of wheat grain and residue benefited from and was higher when bean was the previous crop. However, corn grain yield and residue production always exceeded those from bean. Contribution of wheat (a C_3 plant) to $\delta^{13}C$ of soil relative to that of corn (a C_4 plant) increased with increased N-fertilizer rate. Corn residue yield doubled as N rate increased from N0 to N2 while wheat residue yield tripled. The $\delta^{13}C$ of soil suggested deeper distribution of crop residues with CT than for NT. Changes in C/N ratios indicated that CT systems mixed crop residue and less decomposed SOM with depth in the soil profile, a response consistent with incorporation of plant material by tillage. Much less crop residue was produced under WB-NT than under WC-NT so that less residue C was available to be sequestered as SOC. Highest rate of SOC sequestration was under WC-NT and when increases in SOC from 1994 to 1999 were annualized was 1.0 and 1.9 Mg SOC yr^{-1} in the 0–15- and 15–30-cm depths, respectively. Corresponding SOC in 0–15- and 15–30-cm depths in the WC-CT treatment was 0.2 and 0.6 Mg yr^{-1} and amounts in all other treatments were equal or lower than those observed for WC-CT. Results from this study indicate no-till on N-fertilized WC systems can potentially increase SOC sequestration on large areas of irrigated Vertisols in Central Mexico while maintaining high crop yields. Finally, it was estimated that >1.4 Mg ha^{-1} yr^{-1} of aboveground crop-residue production was required to increase SOC in the 0–30-cm depth and that the C sequestration efficiency of crop residues was about 11%.

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